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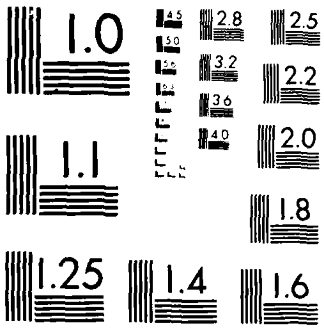

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STUDY OF SEPARATION AND VORTICES
IN ROTATIONAL INVISCID FLOWS

OCTOBER 1986

prepared by

Frank Marconi
Fluid Mechanics Directorate

Grumman Corporate Research Center
Bethpage, New York 11714-3580

Interim Report on
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An investigation of the power of the Euler equations in the prediction of supersonic separated flows is presented. These equations are solved numerically for the highly vortical flow about simple bodies. Two sources of vorticity are studied; the first is the flow field shock system and the second is the vorticity shed into the flow field from a separating boundary layer. Both sources of vorticity are found to produce separation and vortices. In the case of shed vorticity the surface point from which the vorticity is shed (i.e., separation point) is determined empirically. Solutions obtained with both sources of vorticity are studied in detail, compared with each other, and with potential calculations and experimental data.

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Approved by: R. Scheuing
Richard A. Scheuing, V.P.
Corporate Research Center

1. INTRODUCTION

When we began this work, our goal was to understand the appearance of vortices in certain solutions of the Euler equations. In addition we hoped to explore the power of the Euler equations in predicting separated flows. The importance of understanding flow separation and vortices is obvious. The importance of being able to use the Euler equations to predict these phenomena may be less obvious. There are a number of researchers who believe that the issue of vorticity and the Euler equations is moot since some form of the Navier-Stokes equations must be used to study separated flows. The practice of neglecting computational anomalies and complicating the governing equations is dangerous. All the phenomena that we have investigated thus far have physical origins, so that they will exist whether or not the viscous terms are included in the governing equations.

Our research has been successful in answering a number of questions associated with computing highly vortical flow with the Euler equations. A summary of our findings thus far is presented in the text.

2. SUMMARY OF FINDINGS (PHASE ONE & TWO)

Details of the work conducted in Phase One and Two of this effort are discussed in Ref. 1, 2, 3, 4, and 5. Here only the main conclusions will be summarized.

- The vorticity produced by the crossflow shock system in supersonic conical flow can cause separation on its own and may add significantly to the vorticity shed from a separating boundary layer
- As the crossflow shock system becomes weak and approaches a potential (i.e., irrotational) shock, its vorticity no longer causes separation (Fig. 1)
- The reverse crossflow can become supersonic beneath a vortex core and a reverse crossflow shock may form. This shock can cause secondary separation on its own (Fig. 2)
- Increasing eccentricity on elliptic cross sections has a tendency to reduce shock entropy gradients and thus vorticity. Yet, the separation caused by shock vorticity can have a significant impact on the flow field (Fig. 3,4)
- The second-order artificial damping required to stabilize captured shocks does not necessarily significantly distort shock vorticity (Fig. 5). Fourth order damping terms may not be responsible for separation with no apparent source of vorticity[6]
- Both primary and secondary separation can be forced at specified locations by shedding vorticity from a smooth surface. With the vorticity shedding model of Smith[7], the basic features of the separated flow can be reproduced
- In the case of forced separation in supercritical crossflow, the vortex sheet leaves the surface at an angle relative to it causing an oblique crossflow shock (Fig. 6)
- The viscous effects (boundary layer thickening) upstream of separation are much more significant in the case of subsonic crossflow than in the case of supercritical crossflow (Fig. 7 and 8)

- Secondary separation is influenced more by viscous effects than is primary separation (Fig. 8)
- The vorticity shed into the flow field is reduced smoothly as the separation point is moved to its shock induced location (Fig. 9)
- All the results produced in conical flows can be produced for fully three-dimensional flows (Fig. 10). Again the comparisons in the reverse flow region are not very good because of viscous effects. This application of our technique, conducted under our IRAD program, is reported in Ref. 10 and is mentioned here for completeness
- A three shock system (pin-wheel) can be set up around the center of the vortex produced by primary separation (Fig. 11)
- The flow about the leading edge of a flat plate lifting wing will separate as long as the Mach number normal to the edge is subsonic (Fig. 12).

The work with flat plate delta wings is our most recent and is still in progress. It is our feeling that the inviscid flow about a flat plate cannot expand from the lower surface to the upper because the turning angle is beyond the maximum allowed by Prandtl-Meyer theory. With this in mind, it would seem that the only inviscid solution is a separated one and an Euler solver will yield such a solution without the need of a Kutta condition. We have imposed the Kutta condition we have used on smooth bodies on the plate at its leading edge and found some local influence on the surface pressure (Fig. 13). The two results differ only near the leading edge.

It would seem that the Euler solutions for the flow about flat plate delta wings that exhibit flow separation are valid solutions to the differential problem and not associated with any numerical artifices. These Euler solutions seem to suffer from the same problem we have discovered on smooth bodies. That is, the flow under the vortex overexpands relative to experimental results.

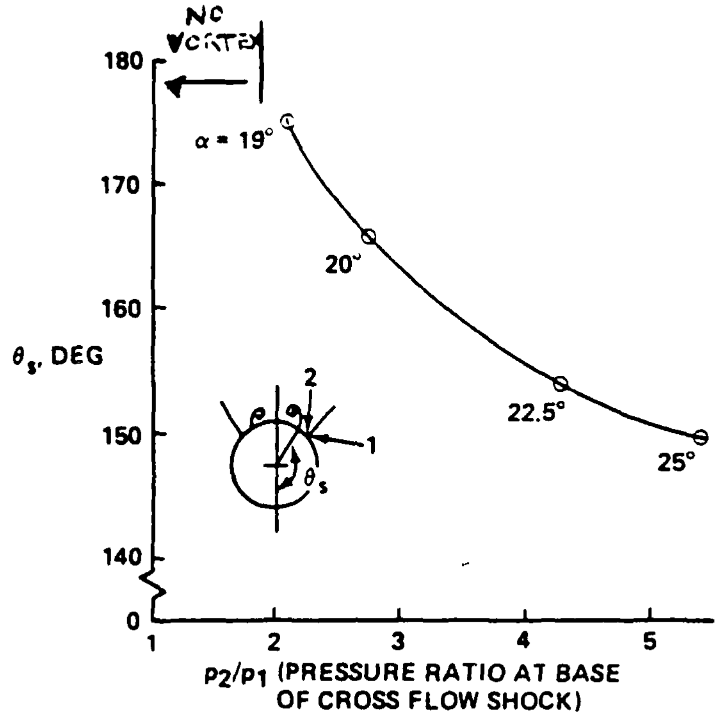


Fig. 1 Inviscid Shock Induced Separation Point Location vs Shock Strength ($M_\infty = 2$, $\delta = 10°$)

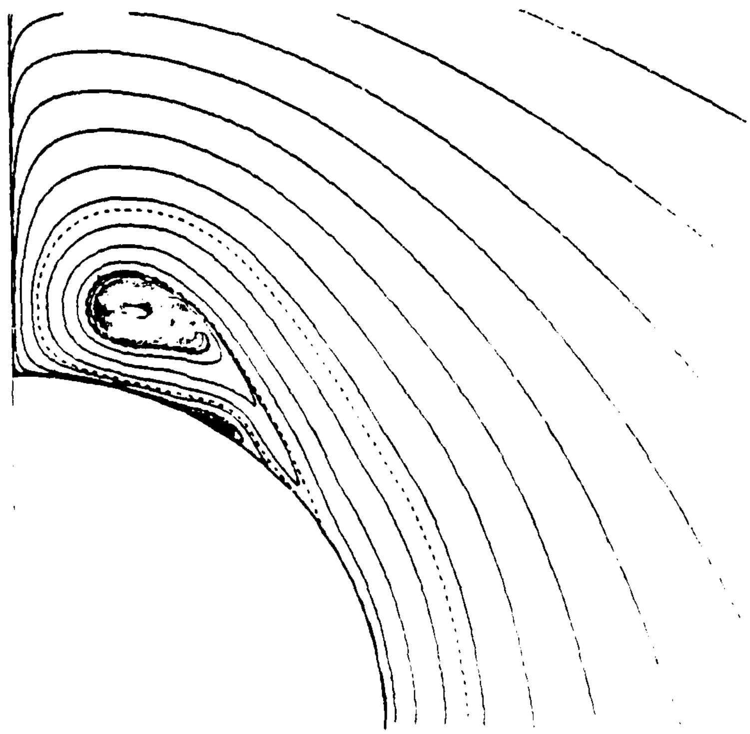


Fig. 2 Crossflow Streamlines, Forced Primary Separation Shock Induced Secondary Separation ($M_\infty = 4.25$, $\delta = 5°$, $\alpha = 12.35°$)

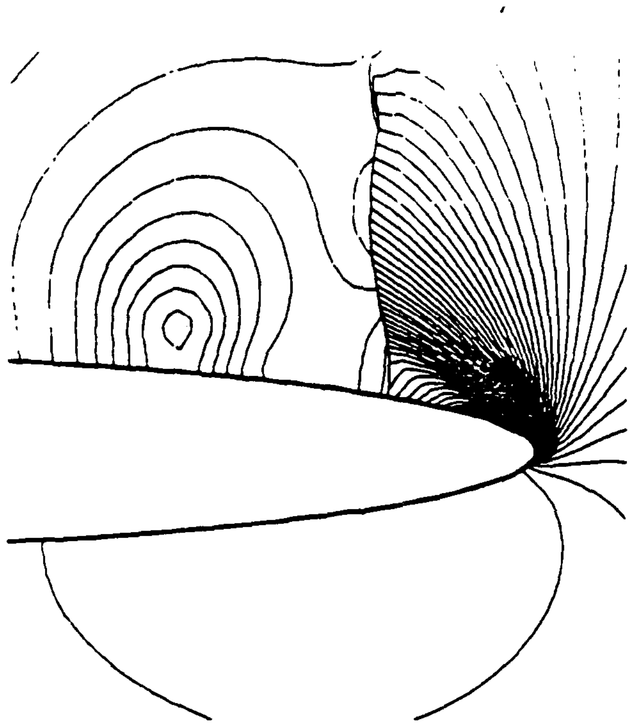


Fig. 3 Isobars Near Leading Edge ($M_\infty = 2$, $\alpha = 10°$, 10:1 Ellipse, $\delta = 1.86°$, $\lambda = 72°$)

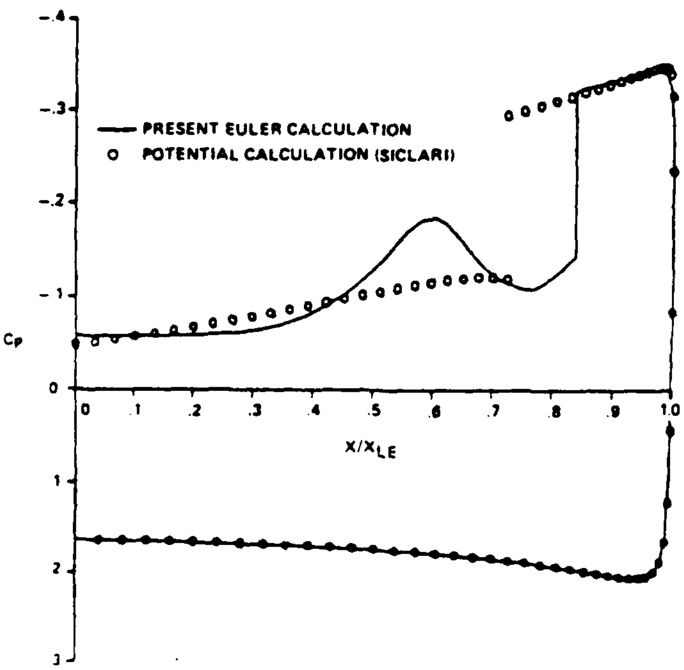


Fig. 4 Surface Pressure Comparison ($M_\infty = 2$, $\alpha = 10°$, 10:1 Ellipse, $\delta = 1.86°$, $\lambda = 72°$)

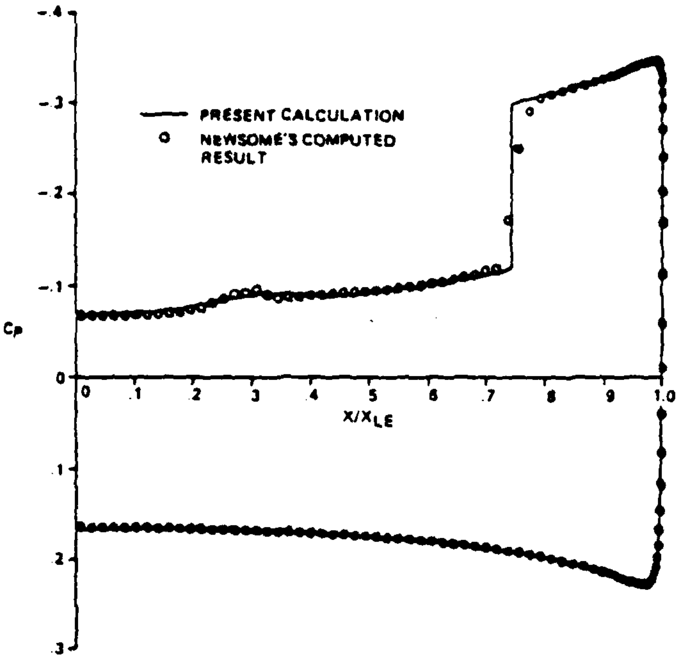


Fig. 5 Surface Pressure Comparison (M_∞ = 2, α = 10°, 14:1 Ellipse, δ = 1.5°, λ = 70°)

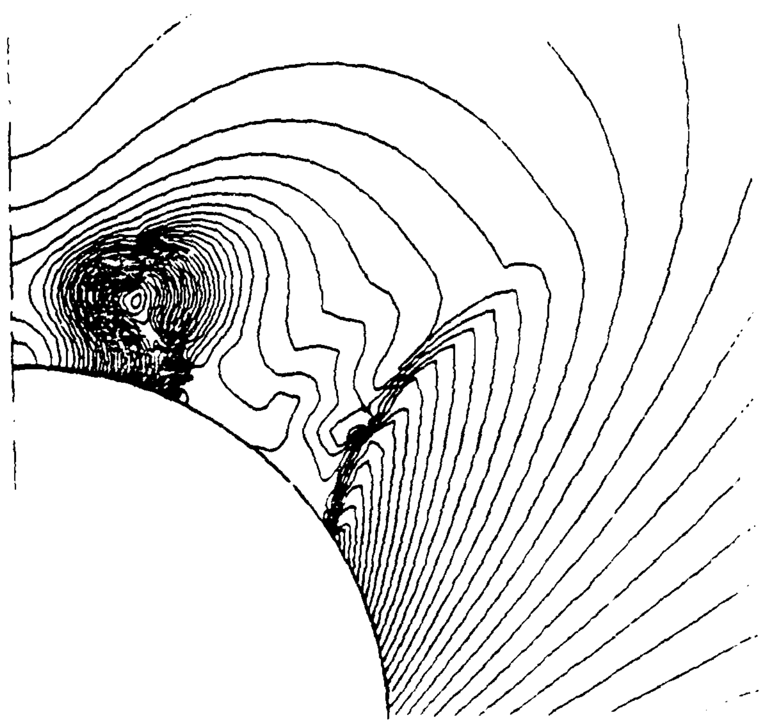


Fig. 6 Isobars, Forced Primary Separation, Shock Induced Secondary Separation (M_∞ = 4.25, δ = 5°, α = 12.35°)

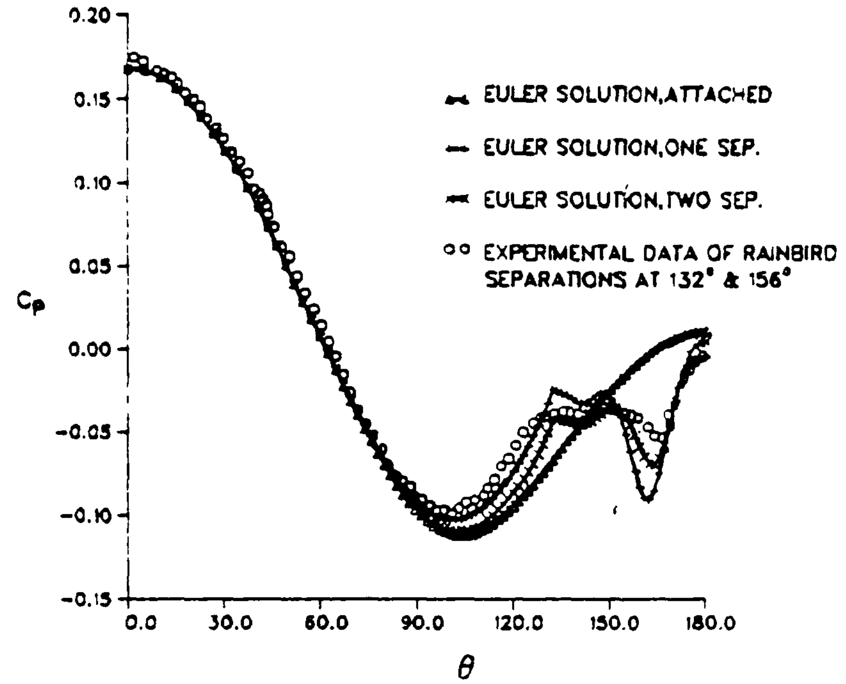


Fig. 7 Surface Pressure Comparison (M_∞ = 1.79, δ = 5°, α = 12.65°) Subcritical Cross Flow

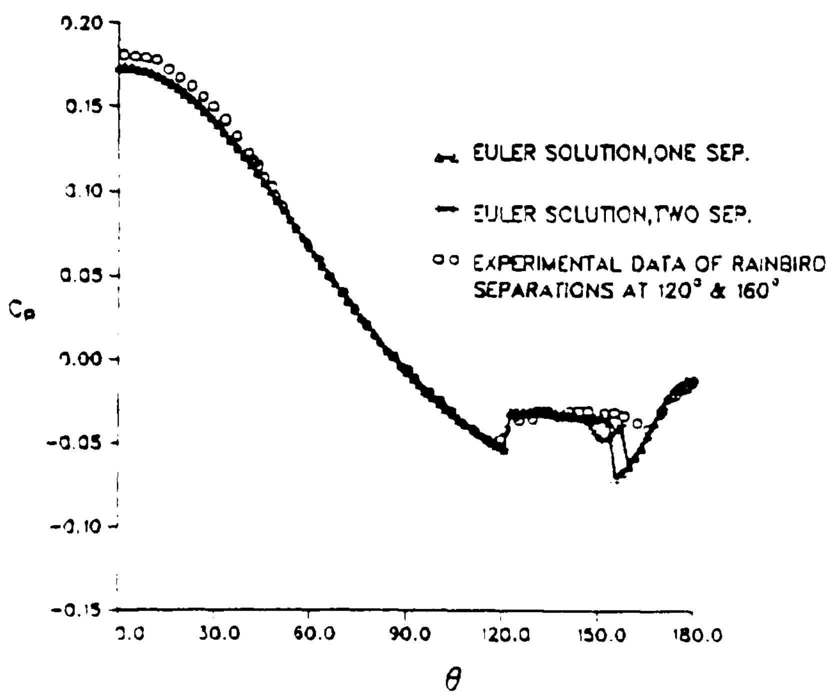


Fig. 8 Surface Pressure Comparison (M_∞ = 4.25, δ = 5°, α = 12.35°) Supercritical Cross Flow

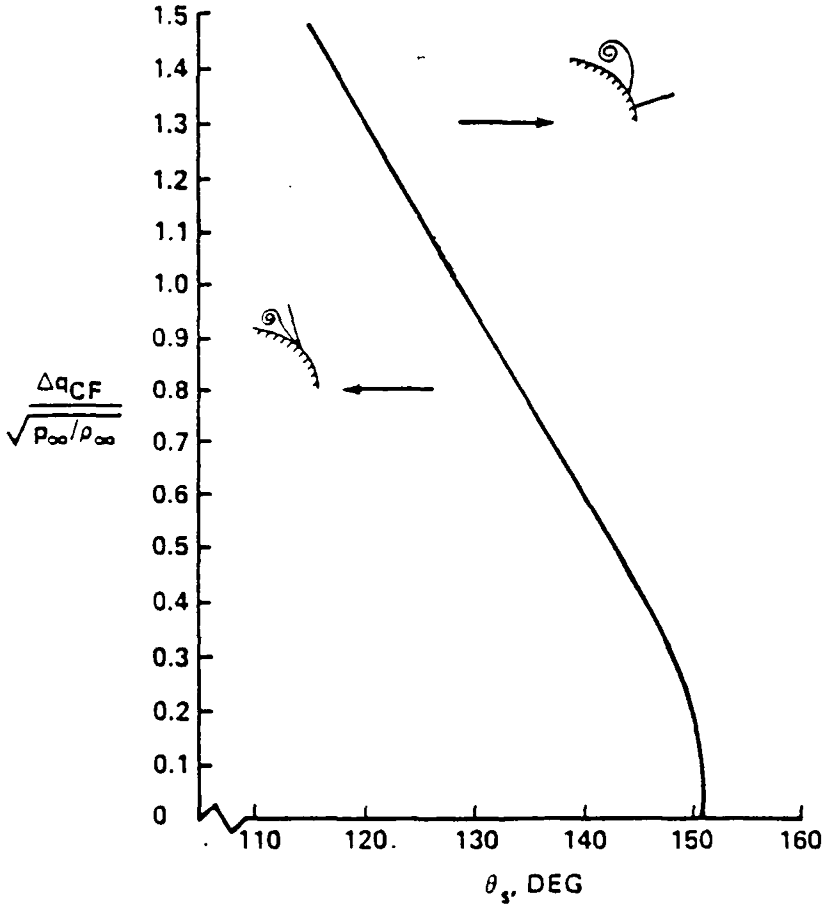
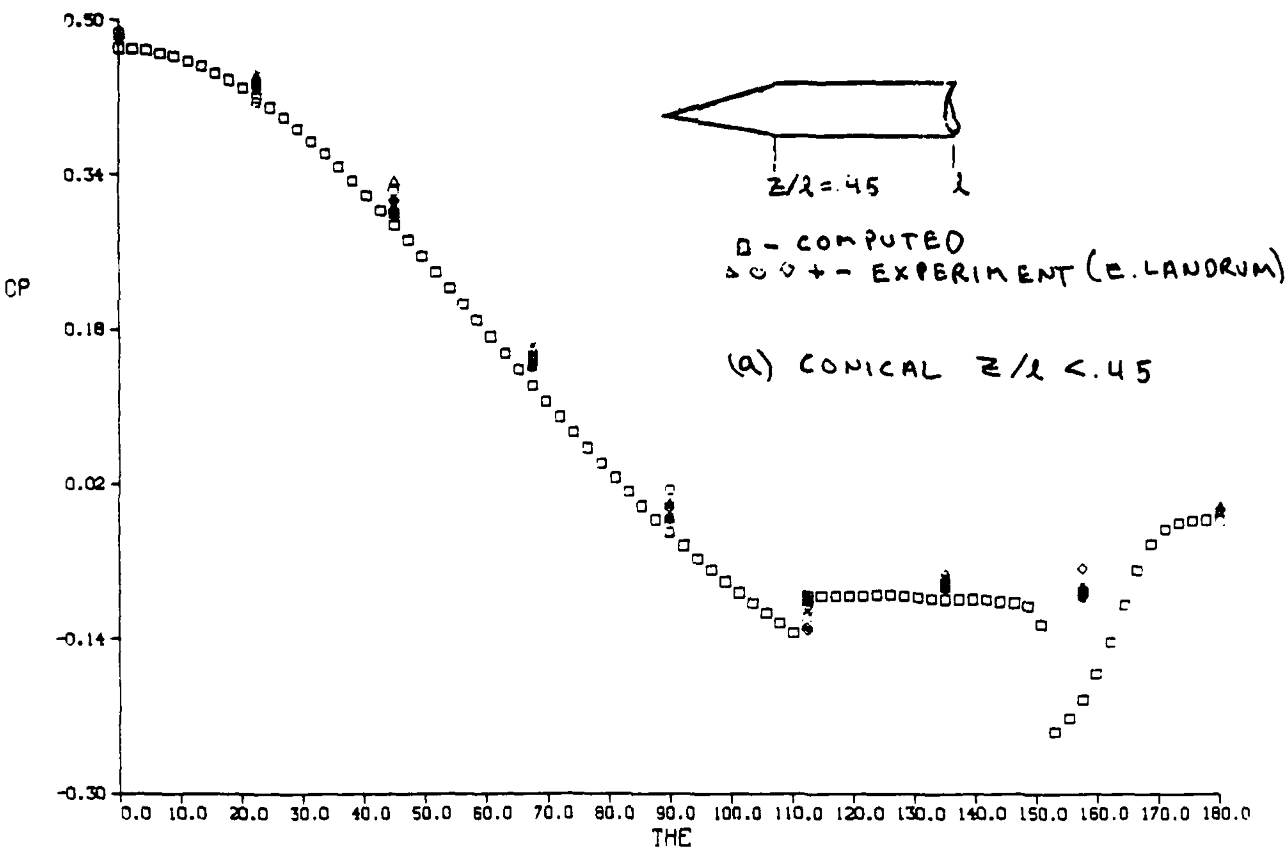


Fig. 9 Vorticity Shed into the Flow Field as a Function of Separation Point Location



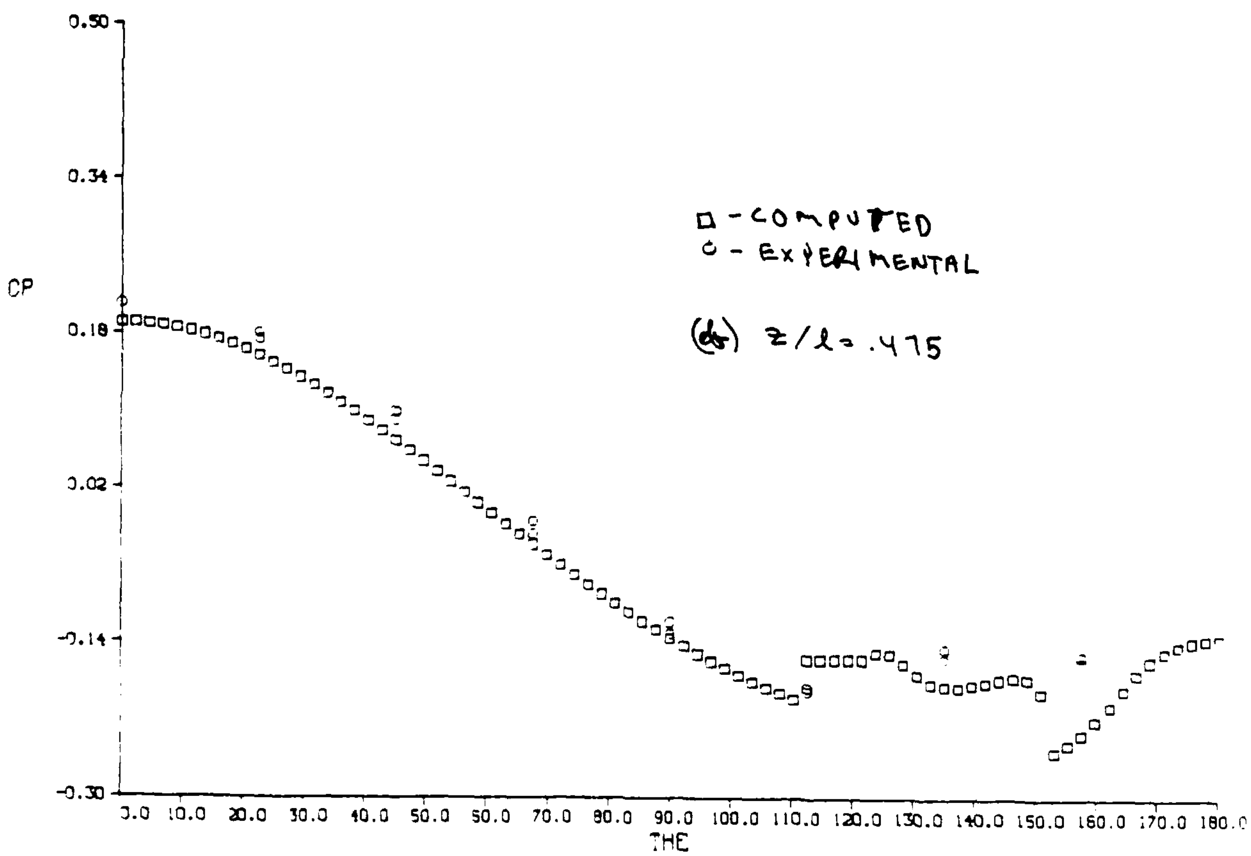
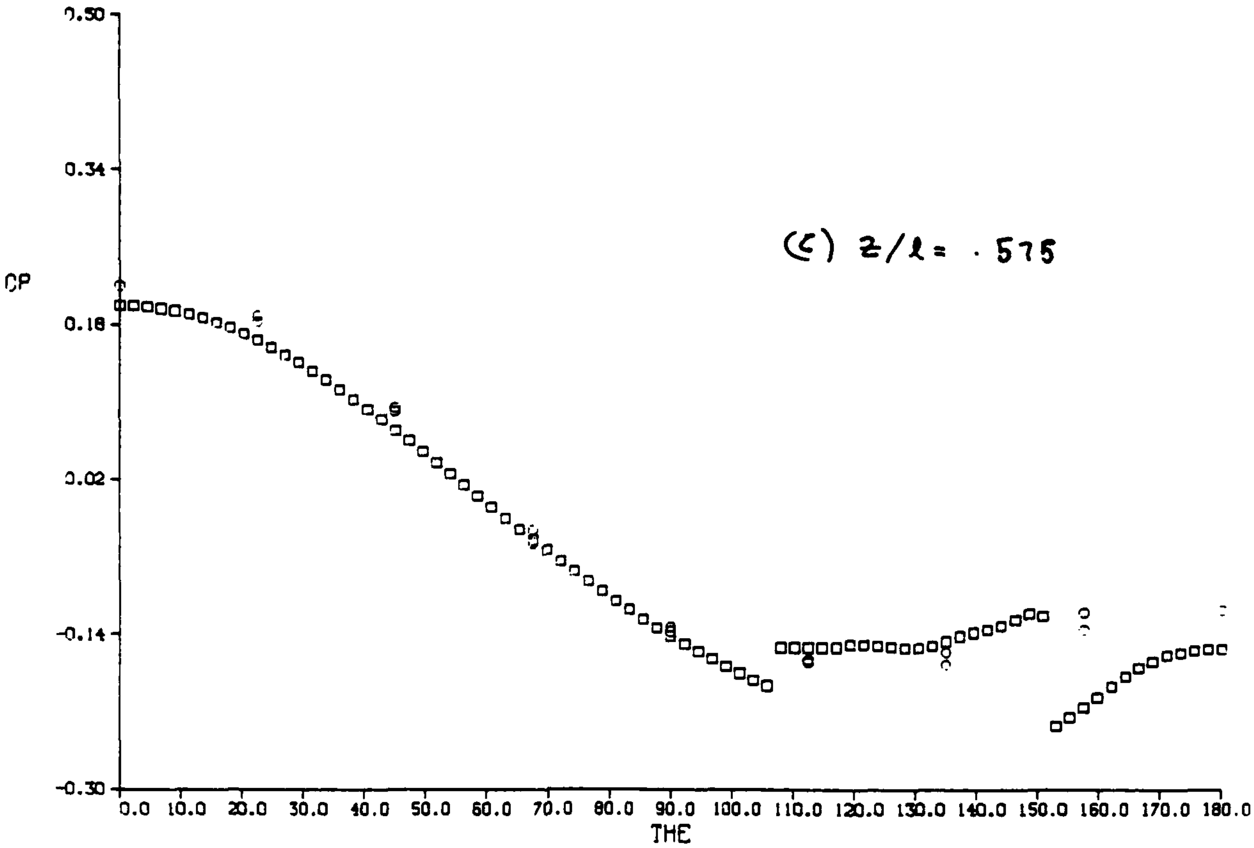
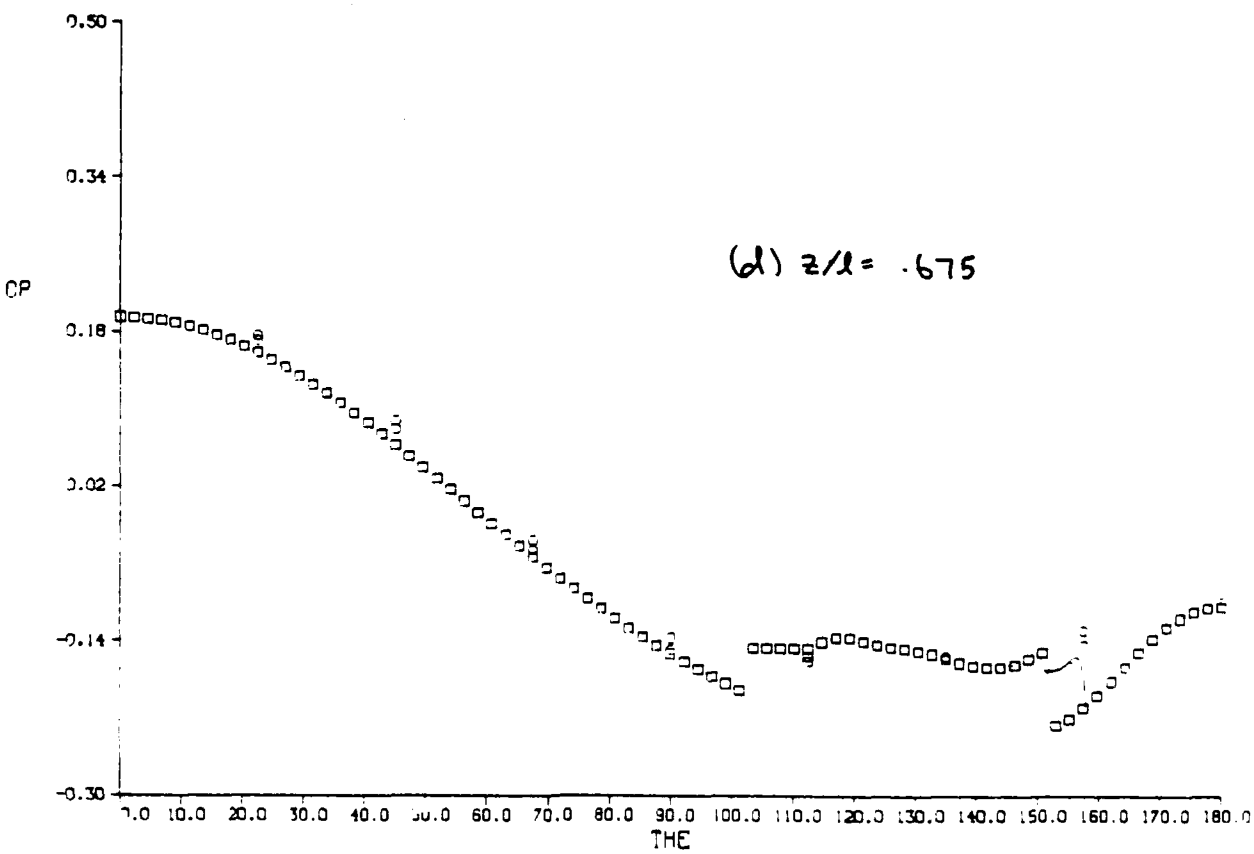


Fig. 10 3-D Cone/Cylinder, Half Angle $\delta \approx 10^0$, $M_\infty = 2.3$, $\alpha = 20^0$, Surface Pressure Distribution





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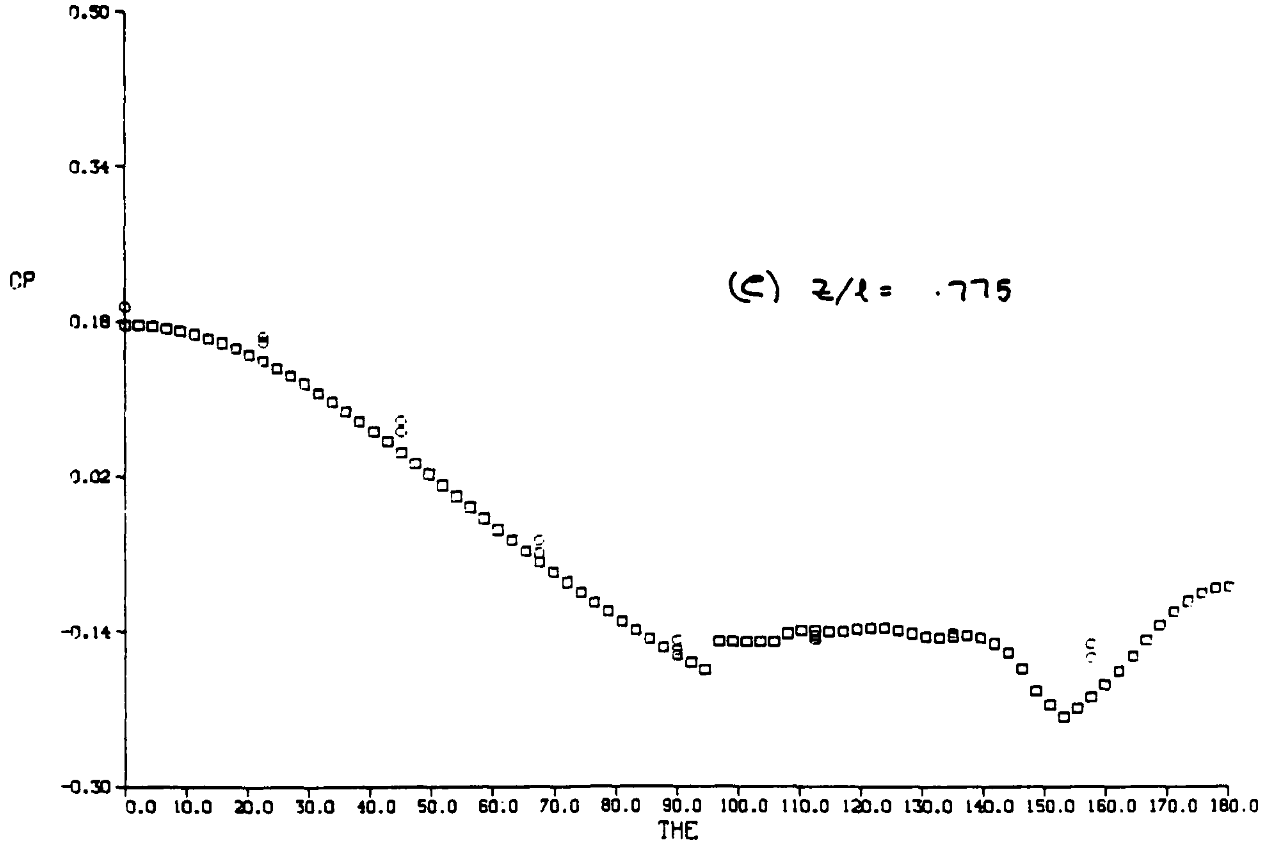

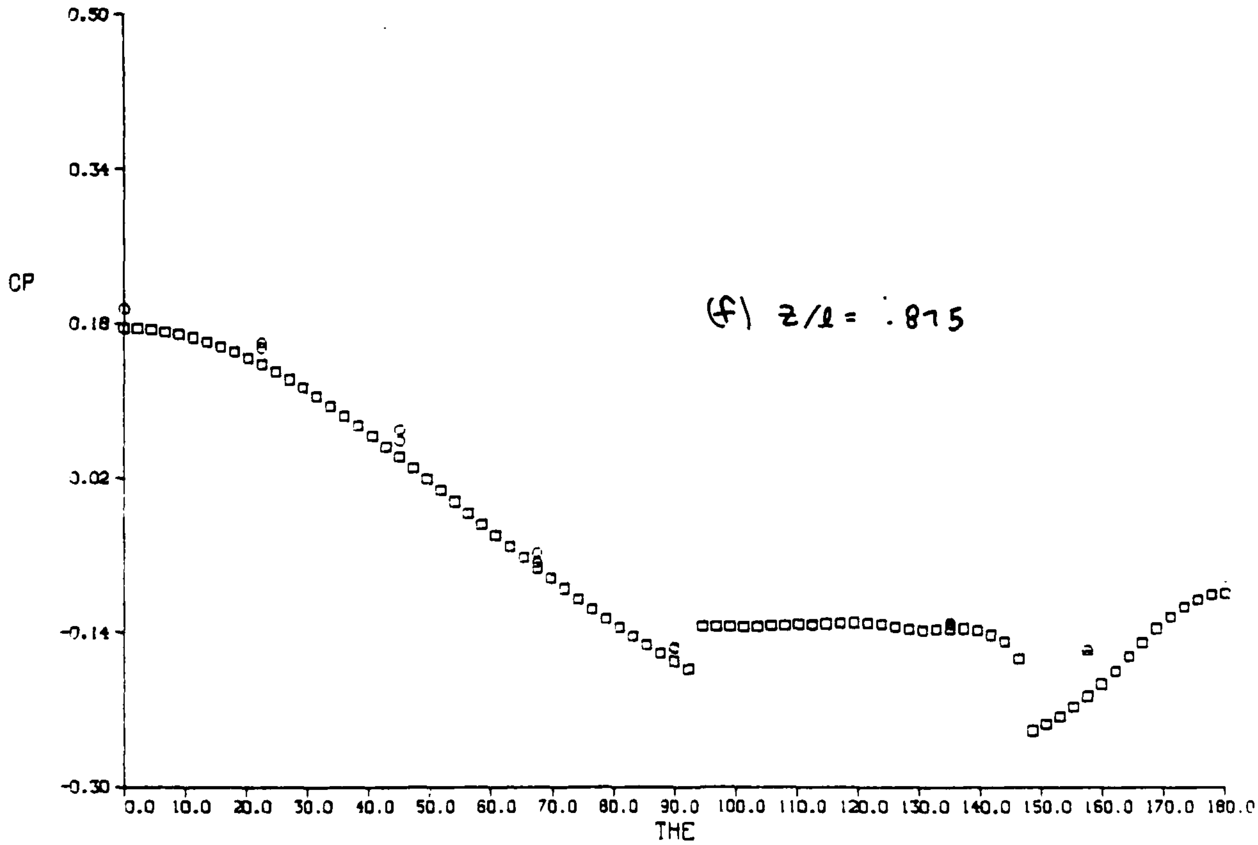

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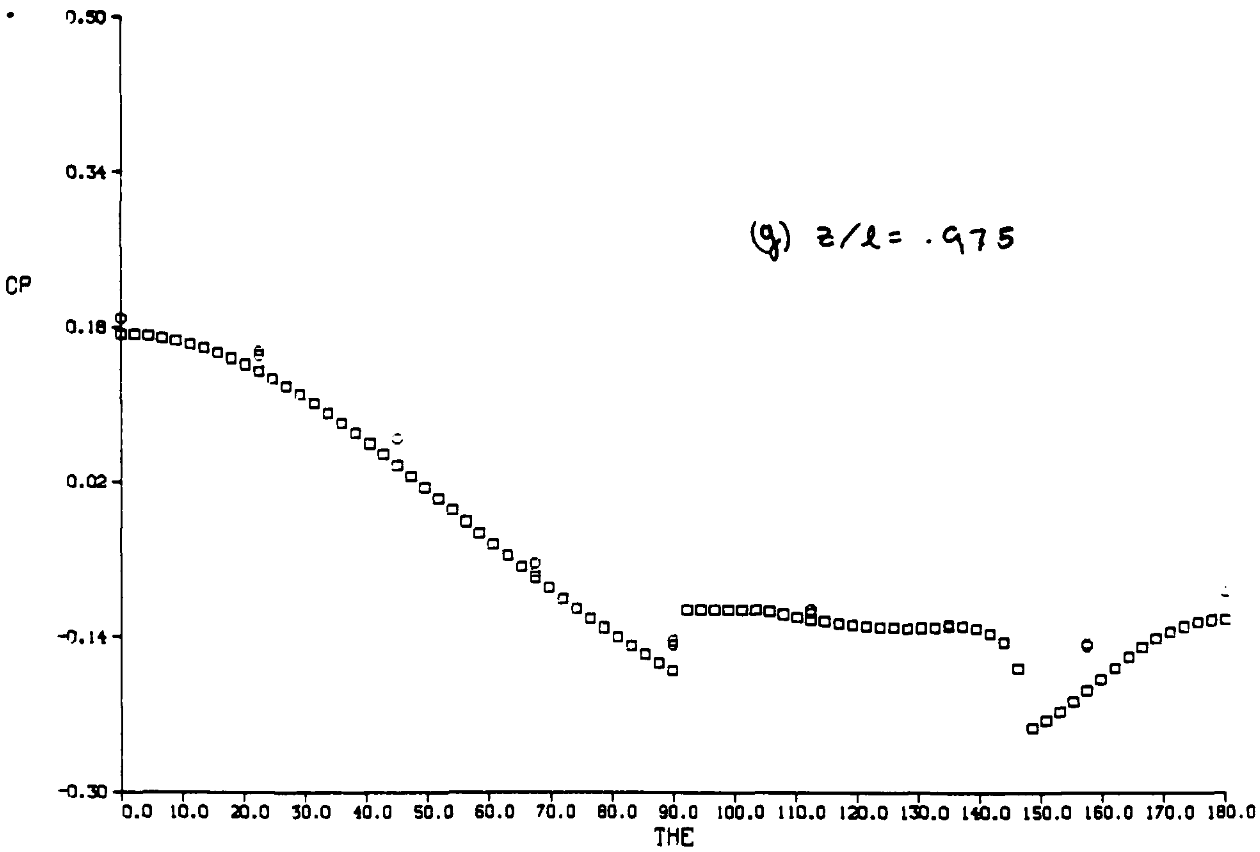

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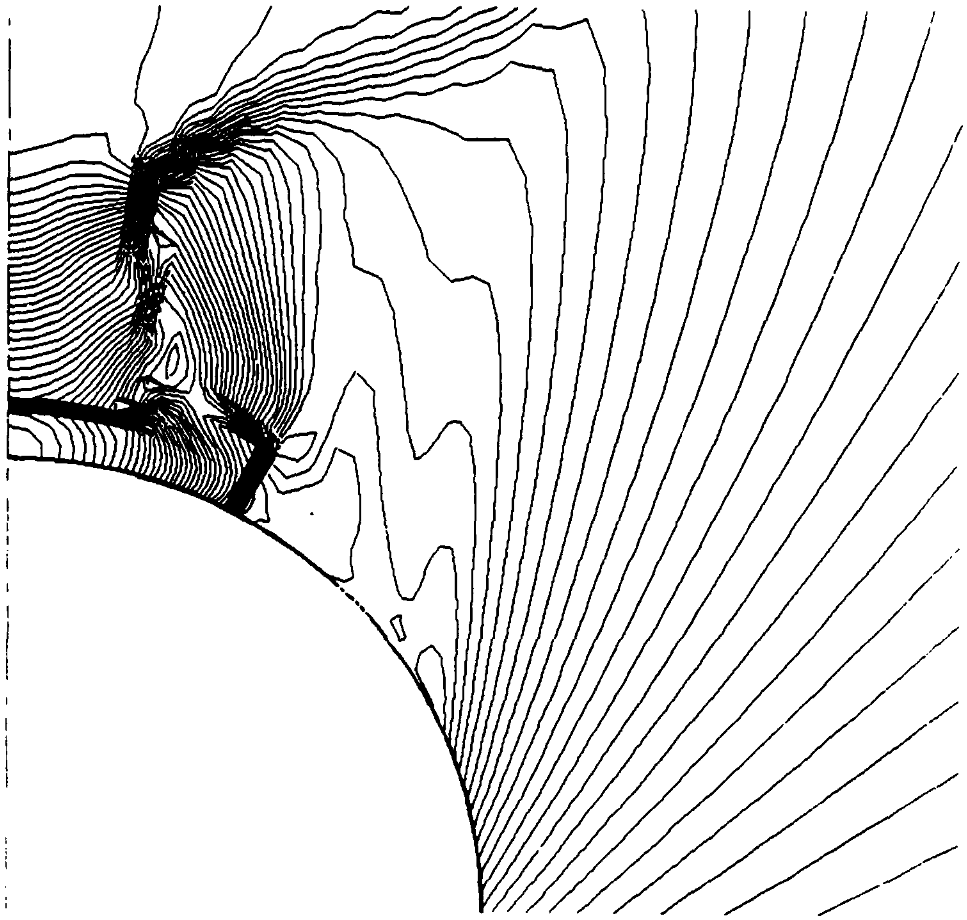

Fig. 11 (a) Isobars, Pin Wheel Shock Pattern
10° Cone, M_∞, α = 36°

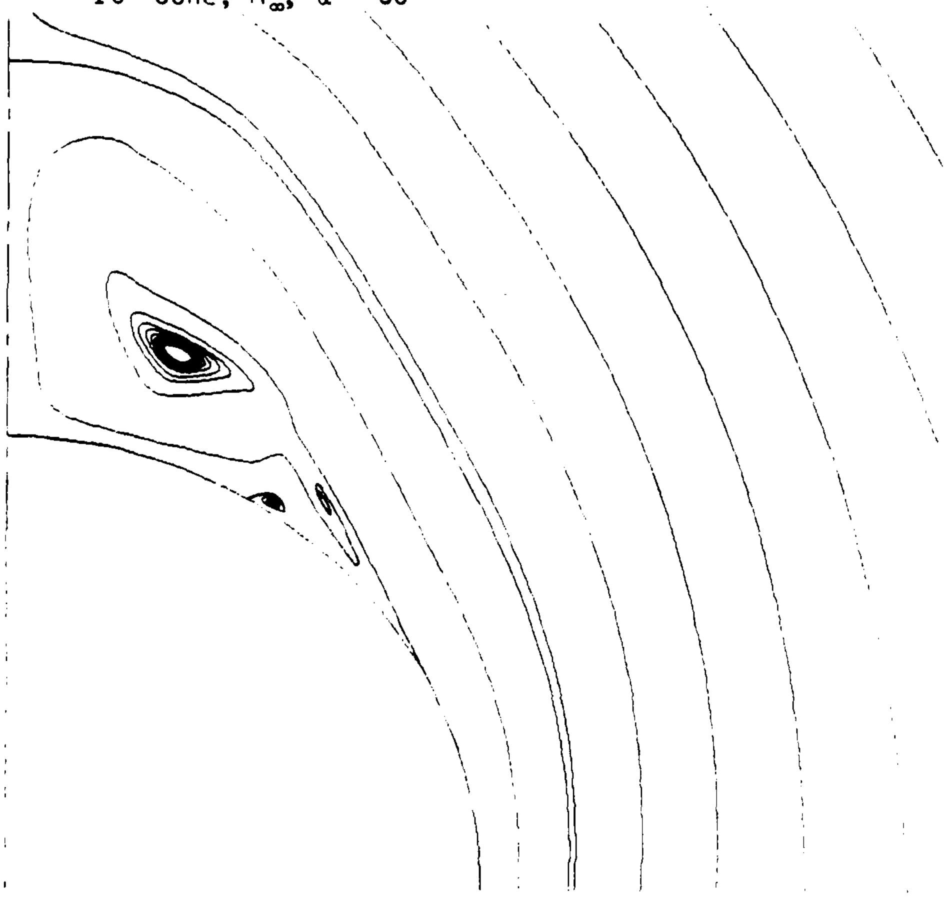

Fig. 11 (b) Crossflow Streamline

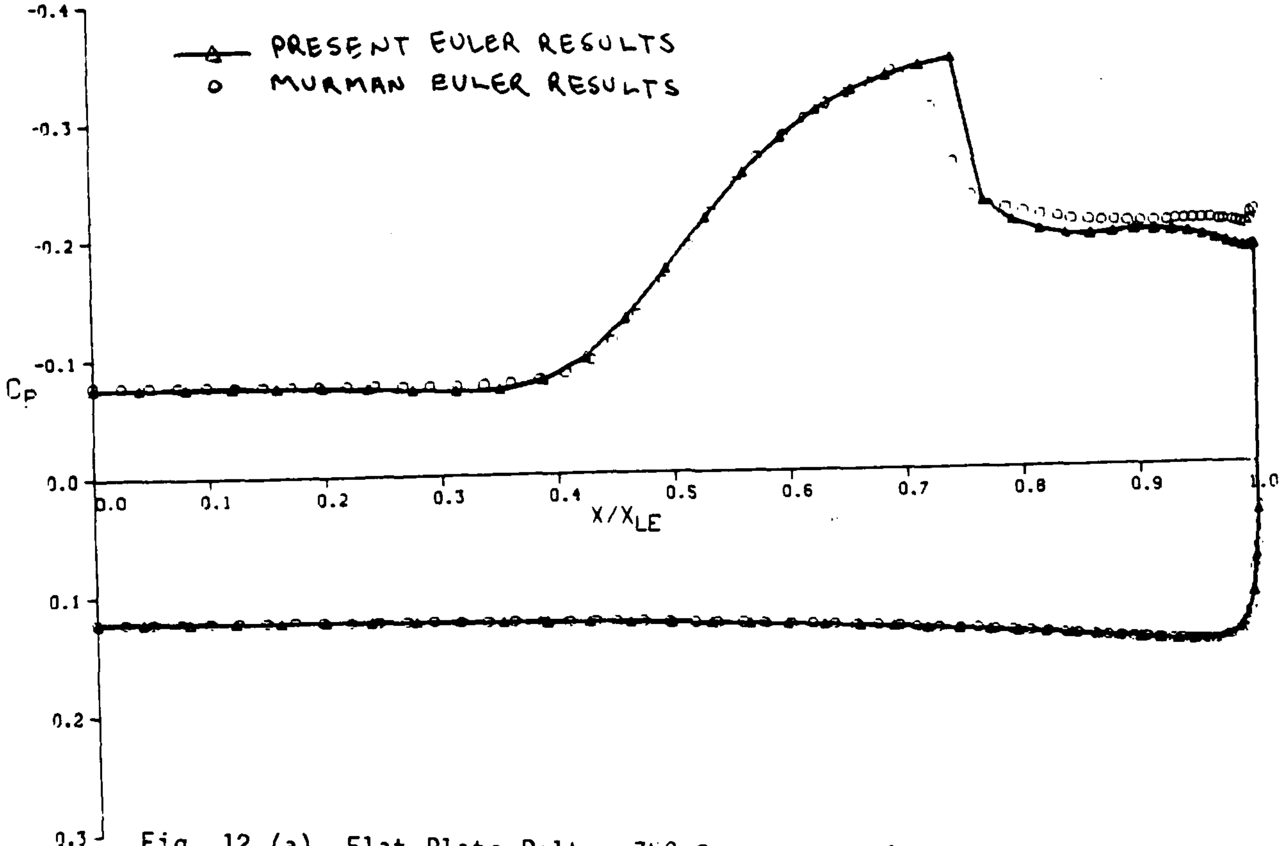

Fig. 12 (a) Flat Plate Delta, 75° Sweep, $M_\infty = 1.95$, $\alpha = 10°$, Surface Pressure Comparison

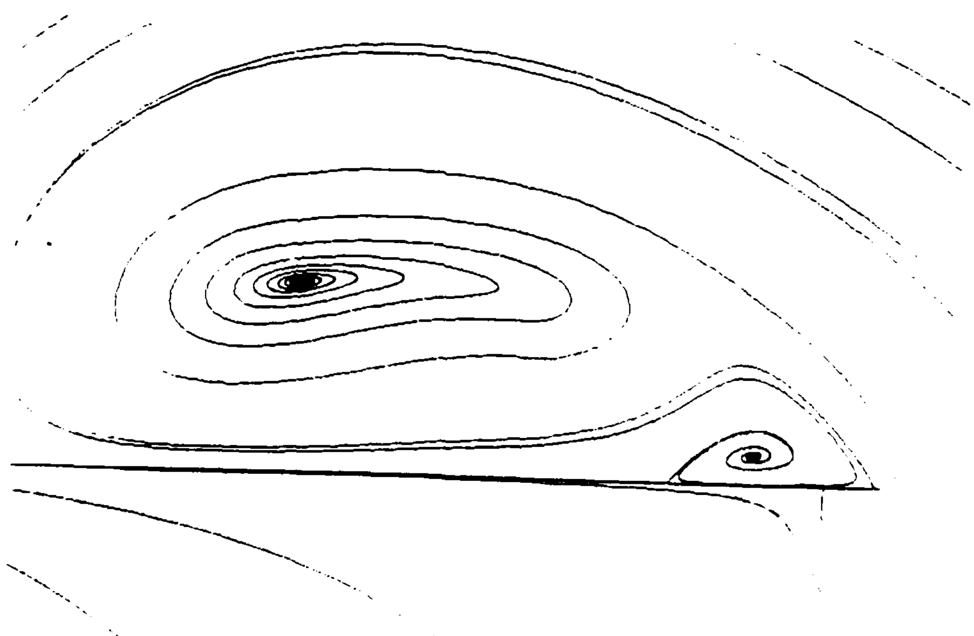

Fig. 12 (b) Cross Flow Streamlines

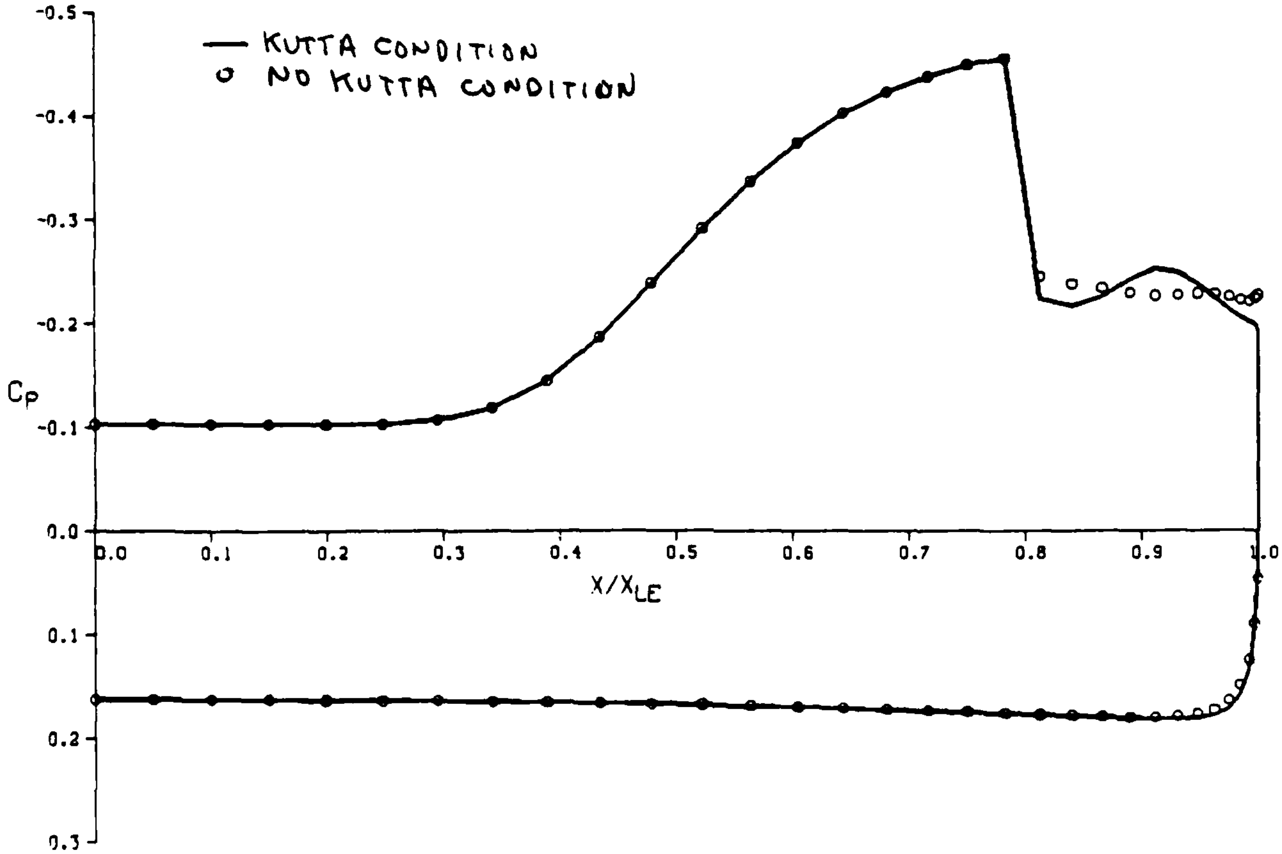

Fig. 13 Flat Plate Delta, 75° Sweep, M_∞ = 1.7, α = 10°, Surface Pressure Comparison With and Without Leading Edge Kutta Condition

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